IN-SCENE ATMOSPHERIC CHARACTERIZATION AND COMPENSATION IN HYPERSPECTRAL THERMAL INFRARED IMAGES

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Compensation of thermal infrared radiometric measurements for atmospheric absorption and emission is one of the main factors limiting the accurate estimation of land surface temperatures and emissivities today. Water vapor, CO_2 and O_3 are the main gases responsible for these effects. Water vapor is concentrated at lower elevations and is variable temporally and spatially in all three dimensions. Carbon dioxide is well mixed and varies mainly with surface elevation. Ozone is concentrated above the troposphere and is therefore insensitive to surface elevation. Ozone concentrations are variable spatially, but only at large scales (e.g., >100 km) and are therefore practically constant over remotely sensed images. Local concentrations of tropospheric O_3 do occur and can influence images.

Because the atmosphere both absorbs and emits thermal infrared radiation, the atmospheric temperature and vertical distribution of active gases must be known at the time of overflight. In practice, this means that the surface elevation must be known and that profiles of atmospheric temperatures and H_2O concentrations must be measured at every pixel, or at least at a scale sufficient to resolve their spatial variability. Clearly, it is currently impractical or impossible to measure atmospheric profiles satisfactorily, by field methods or using other available data independent of the specific image under study. For example, the airborne VNIR/SWIR imaging spectrometer, AVIRIS, is capable of generating estimates of total H_2O vapor on a pixel-by-pixel basis, but not its vertical distribution, nor the temperature distribution. GOES and AVHRR may acquire frequent data at the km scale, but not with sufficient spectral resolution to recover atmospheric profiles. Local atmospheric profiles may be used in conjunction with radiative transfer models such as MODTRAN to predict generalized atmospheric absorption and path radiance, but not with the spatial detail needed for complete compensation.

This impasse has led to the exploration of "in-scene" atmospheric estimation and compensation, using the thermal infrared data themselves to estimate atmospheric profiles. For this purpose, most existing thermal infrared imagers are inadequate. For example, NASA's airborne TIMS acquires data in six bands between 8.2 and 11.7 μm, but these bands are chosen to be in areas of minimum atmospheric effects and thus it is hard to characterize the atmosphere with them. However, airborne imaging spectrometers such as SEBASS acquire data with high spectral resolution (128 bands from 7.5 to 13.6 μm with 30-70 nm bandwidth) over atmospheric bands as well as windows, sufficient to improve estimation of atmospheric absorption and path radiance if not to characterize the atmospheric profiles fully.

We have studied six SEBASS images of an area in the Middle Mountains near Yuma, Arizona, to determine ways to improve local atmospheric compensation with in-scene methods. SEBASS is an airborne hyperspectral thermal infrared imaging system built by Aerospace Corporation around a Rockwell International 128 x 128 "blocked impurity band" focal-plane array. SEBASS data have low NEΔT $\leq$0.05 °K at 300°K) and high spatial resolution (1 mrad or 1.8 m in this case) but low FOV (7.3° or 234 m). The images were acquired from low elevation (1800 m above terrain). The study area is low altitude and low relief (170-240 m amsl) but arid, with atmospheric relative humidity at the percent level. No field data (e.g., radiosonde profiles, solar radiometry, weather data) were available for the Middle Mountains at the time of overflight, 10 am on 20 October 1995.

Our approach to atmospheric compensation has not been formal inversion. Instead, we are currently using a step-wise, "intuitive" inversion method combining successive estimation of atmospheric profiles and MODTRAN modeling of atmospheric transmissivity, path radiance, and down-welling sky irradiance. The ultimate strategy is to estimate a nominal atmospheric profile for each image based on available, largely image-independent data, which is adjusted pixel-by-pixel based on DEM elevations and on information contained internally, in each pixel spectrum. The analysis thus consists of: 1) estimating a nominal atmospheric profile for an entire image; 2) refining that analysis based on in-scene spectral data; 3) modifying the refined estimate, pixel by pixel, based on local elevation and on minimization of residual atmospheric absorption features. We have not yet implemented the complete analysis, although there is no impediment to our doing so. Instead, we have applied the first two steps to the test image of the Middle Mountains, for which the atmospheric variability is minimal.

At each step in the analysis of a pixel, we must compute the SEBASS temperature and emissivity spectrum from the measured radiances, so that the atmospheric effects can be estimated. The temperature/emissivity separation is done using the "Planck draping" method and the assumption that the maximum emissivity is 0.97. This approach has long been used for calculating emissivities from thermal infrared radiance spectra measured on the ground. In it, a blackbody (or graybody) radiance spectrum is computed for an upper limiting temperature, and the difference to the scene radiance spectrum computed. At first, the residual everywhere will be positive, but as the blackbody temperature is successively lowered ("draping" the blackbody spectrum over the scene spectrum), the blackbody and observed spectra will come into correspondence over some range of wavelengths, and there the residual will be zero. If the scene emissivity for this wavelength region has been estimated accurately, the blackbody temperature and the scene temperature will be the same. The Planck draping approach further requires that there be a region, which we have taken to be between 10.8 and 12.2 μm, in which the emissivity is essentially constant and at its maximum value.

The first step in the atmospheric compensation is to estimate a nominal atmospheric profile from available data. The atmospheric profiles were defined for 1-km-thick slices of the atmosphere. Default MODTRAN atmospheric profiles (summer, mid-latitude, low aerosols) with 2.5% surface relative humidity were used initially, but Radiosonde profiles proved more satisfactory, even though they were taken in Death Valley and on a different date (June). The Radiosonde data were used to define the water-vapor profile and the shape of the temperature profile, but the air temperature at the aircraft was estimated from the temperature (295 K) of the "ambient" calibration blackbody (which was inside the fuselage), and the air temperature at ground level was estimated from the apparent temperature (306 K) of resolved desert vegetation (palo verde trees).

SEBASS emissivity spectra of vegetation, which can be expected to at least approximate a graybody, showed that the single biggest atmospheric effect was absorption by H_2O at wavelengths just outside of the 8-12 μm atmospheric window. Also prominent were narrow absorption features near 8.0 μm (H_2O) and 12.6 μm (H_2O and CO_2). The nominal atmosphere assumed in step 1 over-corrected for H_2O absorption, and the relative humidity overall was reduced until the emissivity gradient was zero for the tree spectra. This occurred when the relative humidity at ground level was ~1%. This correction alone, however, was inadequate to remove completely the narrow absorption features.

In step 2 the residual narrow absorption features were minimized by adjusting the temperatures and relative humidities in the nominal atmospheric profile, all in such a way as not to re-introduce a gradient to the recovered emissivity spectrum. This complex adjustment is necessary because absorption by water vapor is temperature-independent, whereas emittance is proportional to temperature. With it, we were able to reduce the amplitude of the residual features near 8.0 μm from about 0.025 to 0.01 emissivity units; however, those near 12.6 μm remained essentially unchanged. It is unlikely that further improvement with this approach is feasible, possibly because the data themselves have artifacts due to reflection from the SEBASS telescope onto the imaging slit. This source of error has been corrected, and the next generation of SEBASS images should be free of it.

Step 3 is the fine-tuning of the atmospheric compensation, pixel by pixel, using DEM and spectral data. If the topographic relief is large enough to require pixel-by-pixel correction, the image data must be registered to a DEM. SEBASS is essentially a nadir-looking instrument; therefore, the differences in transmissivity and the two emittance terms can be interpolated from MODTRAN results for the extreme surface elevations in the scene, regardless of pixel location in the image. In the case of the Middle Mountains scene, however, the surface elevation range was sufficiently low that pixel-by-pixel topographic correction could be overlooked and the nominal scene elevation was used everywhere. As mentioned above, the pixel-by-pixel tuning for variable humidity or temperature was overlooked in this preliminary experiment also.

In this study we focused on tuning the compensation for atmospheric water vapor and temperature. Carbon dioxide affects mainly the longer wavelengths for which SEBASS measurements are the least reliable, and is well mixed and therefore easier to account for. Ozone had negligible influence on the low altitude SEBASS measurements, but in orbital data its compensation needs to be investigated.

The significance of our study is that it shows, albeit for favorable circumstances, that it is feasible to make significant improvements in atmospheric compensation using a simple (if computationally inefficient) approach relying only on internal radiance data and readily available independent estimates of atmospheric conditions. Undoubtedly, compensation will prove more difficult in humid conditions, or from higher altitudes, or in rougher terrain. Nevertheless, it is reasonable to expect that refinements in the algorithm, or a more rigorous, physically based inversion for atmospheric parameters, will at least partially offset these anticipated setbacks. This effort is worthwhile to make: without accurate atmospheric compensation it is unlikely that reliable, generalized scene classification and composition identification based on thermal infrared data is feasible, regardless of the dimensionality of the data. Accurate land-surface temperature recovery, too, requires atmospheric compensation, but to a lesser degree because temperature estimates can be made from those spectral bands least affected by the atmosphere. Our results suggest that in remote sensing the spectral background against which the observations are made may be as important as the measurements of direct interest: the practical consequence of this is that, in future airborne and spaceborne imagers alike, it may be necessary to collect data outside the main thermal infrared window in order to characterize the atmosphere, and to collect at least some data at a spectral scale sufficient to resolve the narrower atmospheric bands as well as the broader surface reststrahlen features.